Reliability of ground reaction forces in the aquatic environment

1. Introduction

Bipedal gait is a skilled and complex activity that requires coordinated and controlled movements of the limbs, which act alternately from one support position to another. Gait can be studied and evaluated in various ways, one of which is through the use of force plates (FPs) that measure the direction and magnitude of the ground reaction forces (GRFs) (Duarte and Freitas, 2010). GRFs are of equal magnitude and the opposite direction to the force the body exerts on the ground through the foot, and must be overcome during forward movement (Sutherland, 2005).

Aquatic exercises are widely used in the treatment of patients with many different medical conditions; these exercises maximize the properties of water related to fluid mechanics, such as viscosity, drag force, turbulent flow and buoyancy to achieve best outcomes for patients. Water is an ideal environment for exercise due to the decreased weight bearing through the lower limbs, offering less impact throughout the stance phase of the gait, but exercise in water also requires greater propulsive force to overcome the force of water (Harrison and Bulstrode, 1987; Nakazawa *et al.*, 1994 and Barela *et al.*, 2006).The magnitude of the gait GRFs although lower than on land, can still be excessive, depending on the individual patient and their condition or medical problem. Knowing the GRFs related to different underwater activities during rehabilitation would help in exercise prescription and the evaluation of patients in this environment (Haupenthal *et al.*, 2010c).

In 1992, Harrison *et al.* investigated GRFs in the aquatic environment. The authors designed a waterproof FP using a silicon rubber compound to measure weight-bearing during underwater gait at two heights of water submersion (1.1 and 1.3 m) and patients walked at two different speeds (slow and fast). The authors found that the percentage of weight bearing decreases inversely proportional to the speed. Since this seminal work, several other studies have explored GRFs in water during different activities such as running, jumping, backward walking and stationary running, factors such as depth of immersion and gait velocity have also been considered (Haupenthal *et al.*, 2010a; Haupenthal *et al.*, 2010b; Orselli and Duarte, 2011; Fontana *et al.*, 2011; Donoghue *et al.*, 2011; Carneiro *et al.*, 2012; Fontana *et al.*, 2012 and Haupenthal *et al.*, 2013).

The use of reliable methods to determine the outcome of clinical interventions is essential as outcomes (or lack of outcomes) can have serious implications for patients. Visual and observational assessment methods are subjective and may not accurately reflect the results of treatment intervention. Thus, reliability studies are needed to evaluate the error in any outcome measure and test-retest studies are required to determine how well any measure performs at different times (Rankin and Stokes, 1998). Such studies may provide data about consistency as well demonstrating the safe use of the outcome measure not only in clinical practice but also in biomechanics research (Portney and Watkins, 2000 and Lexell and Downham, 2005).

Several studies have evaluated the reliability of the FP during gait on land in different conditions and with different populations (Kadaba *et al.*, 1989; Hamill and McNiven, 1990; White *et al.*, 1999; Fortin *et al.*, 2008 and Veilleux *et* *al.*, 2012). However, to date there are no studies assessing the reliability of the FP in underwater walking. This is a major gap in the literature considering the extent to which aquatic exercises are used in rehabilitation and the need for a reliable outcome measure. The immersed body is affected by the action of fluid mechanics, which of course influences gait, thus establishing the reliability of kinetic parameters of underwater gait is necessary. The aim of this study therefore was to investigate the test-retest reliability of the kinetic gait parameters, as measured by a FP, in healthy individuals in water.

2. Method

2.1 Participants

Forty-nine healthy young volunteers participated in this study, 31 females and 18 males, with a median (Md (25-75%)) age of 21 years (20-22), mass of 57.5 kg (53-68), weight in the water of 147 N (98-225.5) and height of 1.65 m (1.60-1.72). The volunteers were considered eligible if they were between 18 and 24 years and had no current lower extremity musculoskeletal pain and/or injury or any disorder affecting sensation in the lower extremity that may affect gait. Volunteers who did not meet these inclusion criteria were excluded. All participants were notified of the procedures and requirements and were invited to participate by signing an informed consent form. The study and all procedures were approved by the Ethics Committee of the UEL (#217/2012).

2.2 Instrumentation

Data were collected using a waterproof force platform (Bertec Corporation®, model FP4060-08-2000), with dimensions of 0.6X0.6X0.1 m, sample rate of the acquisition system of 1000 Hz, capacity of Fz = 5000N and Fx = Fy = 2500 N and 340 Hz (Fz) and 550 (Fx = Fy) of natural frequency with a 16-bit A/D converter. The FP was placed in the final third of a 10 meter pool, located in the Aquatic Physical Therapy Center “Prof. Paulo A. Seibert”, with dimensions of 15x13x1.30 m, extent of submersion around 1.20 m and water temperature of 32.5 °C.

2.3 Procedure

The individuals walked on the platform at a self-selected speed, and were asked to walk onto it with their preferred leg. The test was repeated three times or until three valid data recordings had been collected. A trial was considered successful when only one foot made contact with the platform (Figure 1); trials not meeting these criteria were excluded and another trial was performed. Participants were instructed to walk normally while looking straight ahead and not to look at the platform.

Before starting data collection, participants practiced walking across the platform until they were comfortable with the procedure. The gait cycle started with initial foot contact with the force platform and ended when this foot left the platform. For the test-retest reliability, two recordings were performed with a 48-hour interval between them.

2.4 Data Processing

Force plate data were analyzed using a specific routine in Matlab® 7.9.0 (R2009b, Mathworks, TM), smoothed by a Butterworth low-pass filter of 4^{th} order and cutoff frequency of 5 Hz defined by spectral analysis (Carneiro *et al.*, 2012, Haupenthal *et al.*, 2010b and Miyoshi *et al.*, 2004).

The analyzed GRF components were the vertical (Fz), anteroposterior (Fx) and mediolateral (Fy). Maximum and minimum values were selected from the curve profiles to assess the reliability of gait parameters. For the Fz component, the first peak is the response to load (Fz1), the second point is the valley and represents the average support (valley) and the second peak represents the terminal support (Fz2) (White *et al.*, 1999). For the Fx component, the point selected represents the phase-end or maximum propulsion. Two points were considered for the Fy component, the first peak (Fy1) represents a lateral thrust during loading, during which time the foot is moving from a supinated position into pronation and the second peak (Fy2) is a small lateral force often seen during the final push off stage (these parameters are demonstrated in Figure 2) (Miyoshi *et al.*, 2004 and Richards, 2008). Furthermore, the acceptance rates (AR) which correspond to the curve slope during the loading phase were analyzed, calculated by dividing the value of the response to load by the difference between the beginning and the force peak (Fz1/Δt), as well the propelling charges which are given by dividing the Fz2 by the time difference of the peak and the valley (ΔFz2/Δt) (Sacco *et al.*, 2012).

To set the gait cycle, the mean and standard deviation (SD) of the baseline from the Fz data before foot contact were calculated. Thus, the beginning of the gait cycle was defined as the local minimum of the curve, which preceded the moment at which the Fz exceeded the mean value of the baseline added to four standard deviations.

Data were normalized by body weight of the subject. An example of a normalized profile curve can be seen in Figure 2. For the reliability analysis, the average value of the three trials of each component was employed (Grainger *et al.*, 1983 and Diss, 2001).

2.5 Statistical analysis

As the normality assumption for the data was not met, data are presented as median (Md) and quartiles (25-75%). The test-retest reliability was assessed by calculating the intraclass correlation coefficient (ICC) (one-way random effect model) and the agreement analysis proposed by Bland and Altman (1986). An ICC value < 0.4 was considered as poor reproducibility, 0.4 ≤ ICC ≤ 0.75 indicates fair to good reproducibility and > 0.75 indicates excellent reproducibility (Fleiss, 1986).

The Bland-Altman agreement was incorporated with the mean difference ($\bar{d}$) and their respective 95% confidence intervals (CI), the SD of mean difference (SD of $\bar{d}$) and the limits of agreement (LA) analyses. In addition the value of the SEM (standard error of measurement) was calculated through the ICC, using the number of errors that can be allocated in the sample; SEM was calculated using the equation SD x$\sqrt[2]{1-\mathrm{ICC}}$ (Jewell, 2011). In addition, the Wilcoxon test was conducted to compare the forces from the first and the second test in order to evaluate the effect of familiarization on the results.

Analyzes were performed in the programs IBM SPSS (Statistical Package for Social Sciences, version 22; Armonk, NY: IBM Corp.) and MedCalc Software bvba (version 15.6.1; Ostend, BE).

3. Results

The values for the vertical component of the GRF were expected for an aquatic activity. These values (minimal - maximal) ranged from 0.13 - 0.41 N/BM for the Fz1; 0.03 - 0.37 N/BM for the valley and 0.14 - 0.41 N/BM for the Fz2.

The SEM values were low, indicating that the error incorporated in the data was minimal. In relation to the GRF values in the test-retest, statistical differences were found for the Fz1 and Fz2 and no differences for the other parameters (valley, Fx, Fy1, Fy2, AR and PR), which shows that the subjects were able to reproduce the same speed in both tests (Table 1). Despite the differences found for Fz1 and 2, the values for response to load and terminal support, in terms of interquartile range, are alike and moreover, does not seem to be relevant in practice.

The test-retest results demonstrated a reliability ranging from poor to excellent for the ICC values and a mean difference close to zero for all parameters. For the Fz and Fx components the reliability values were excellent, while for the rate of acceptance and propulsion was considered good. For the Fy component, the reliability was also good for Fy1 and poor for Fy2, despite this the mean difference was also low, showing that the two measures (test-retest) were similar. Further information about ICC and mean difference can be found in Table 2 and in Figures 3 to 6.

4. Discussion

The aim of this study was to investigate the test-retest reliability of kinetic gait parameters, as measured by a FP, in healthy individuals in water. The results demonstrated variability in the ICC values from 0.24 to 0.87, ranging from poor to excellent. Since the calculation of the ICC in isolation does not provide enough information about the reliability of the measurements, the values generated in the Bland-Altman plots and SEM were used to complement the ICC (Rankin and Stokes, 1998).The identified SEM values in the present study were close to zero, indicating that the number of errors attributed to the sample was low (Jewell, 2011). When the difference between test and re-test was analyzed, it can be observed that there was an increase in Fz 1 and 2. It is possible that this may be due to the practice effect, however, the values for response to load and terminal support, in terms of interquartile range, are alike and moreover, this does not seem to be relevant in practice.

The findings of this current study support the findings of Fortin *et al.* (2008) who evaluated the repeatability of gait parameters individuals with scoliosis. These authors reported that the SEM values found for the three kinetic components of the gait were low. The mean difference values identified in this study by the Bland and Altman plots (Bland and Altman 1986) were close to zero for all items, demonstrating little variation among the data.

The component that demonstrated an excellent result for reliability was the Fz, which is similar to previous studies carried out on land, in which the highest values were also found for Fz (Kadaba *et al.*, 1989 and White *et al.*, 1999). In the literature, this component is the most frequently used to evaluate GRF in gait (Amadio and Baumann, 2000). Owing to the action of buoyancy and hence the reduced apparent weight, the forces applied to the force platform are also decreased, with a possible reduction in Fz of 60-70% (minimum of 0.13 and maximum of 0.41 for Fz1; minimum of 0.03 and maximum of 0.37 for Valley and minimum of 0.14 and maximum of 0.41 for Fz2) compared to on land (minimum of 0.91 and maximum of 1.18 for Fz1; minimum of 0.71 and maximum of 0.95 for Valley and minimum of 0.92 and maximum of 1.23 for Fz2). When buoyancy is added to the drag force in water, a lower speed (about 36% compared to on land) can be observed (Barela *et al.*, 2006) and a longer contact time on the FP is generated. Furthermore, lower muscle activity is observed in the water, thus the curve pattern is characterized by less defined peaks (Nakasawa *et al.*, 1994; Miyoshi *et al*., 2005 and Carneiro *et al.*, 2012).

It is mainly through the Fz analysis, that is detected the moment that the heel touch ground (Hreljac and Marshall, 2000; Ghoussayni et al., 2004; O'Connor et al., 2007, Desailly et al., 2009; Asha et al., 2012), allowing a direct relationship between the time of support and the resultant forces of the muscle actions that occur in the lower limbs. As a result, a product of the vector of the GRF is generated and transmitted to the body through the feet, making the vertical component the largest part of the GRF (Winter, 1980). Moreover, it is the component that best represents the GRF with characteristic and consistent graphics, which can provide information about mechanical stress (Piscoya *et* *al.,* 2005). This measure can also characterize joint contact forces, which seem to play an important role in the development of certain musculoskeletal disorders (Piscoya *et al.,* 2005).

For the Fx component, excellent ICC values were identified with low mean difference values, which also supports the findings of published studies exploring GRF on land (Kadaba *et al.*, 1989 and Fortin *et al.*, 2008). When analyzing the variation of the Fx component, in the studies of Miyoshi *et al.* (2004) and Orselli and Duarte, (2011), only positive values (anterior direction) were found, which is consistent with the present study which found positive peaks rather than a negative (posterior direction) valley followed by a positive peak (profile curve commonly found on land). This pattern seems appropriate since, by overcoming all water resistance, participants must generate the gait acceleration phase (Miyoshi *et al.*, 2005), thus altering the gait support phase, tilting the body forward and only stepping on the force platform when their lower limb exceeds the longitudinal axis of the body, eliminating the deceleration phase (Miyoshi *et al.*, 2005 and Haupenthal *et al.*, 2010a). In this current study, only the point of the Fx component (the final peak) was evaluated, this peak represents the maximum propulsion, as the curve profile in water does not allow any other point to be stated with certainty.

The Fy component of gait (medial-lateral displacement) demonstrated the lowest reliability values, probably due to the influence of fluid mechanics, it is known that medio-lateral movements are more unstable compared to anteroposterior (Kuo and Donelan, 2010), which changes the movements of the ankle and causes irregular behavior of this joint (Sutherland *et al.*, 1980; Miyoshi *et al.*, 2005). During gait on land, the ankle joint has an important role in supporting the body weight, however, in the aquatic environment, buoyancy decreases the weight of the individual and consequently there is less necessity for the ankle joint to provide support (Miyoshi *et al.*, 2005; Orselli and Duarte, 2011; Sutherland *et al.*, 1980).

Another possibility for the low reliability of the Fy component may be related to the choice of the peak of the curve that was selected. In water the Fy component does not follow a curve profile as in the case of the other components. The results demonstrated that the Fy component varied across participants, which perhaps suggests that the chosen point on the curve profile may not have been the most suitable, thus increasing overall variability.

During gait, the swing phase leg directly influences the medio-lateral vector of GRFs due to displacement of the body center of mass to the side of the stance leg. In addition, the turbulence generated by the oscillating limb and the reduction of muscular activity in the water can interfere with the amplitude value of Fy (Sutherland *et al.*, 1980; Barela *et al.*, 2006 and Lin *et al.*, 2014). The range of ICC values of Fy demonstrated poor to good reliability (between 0.24 and 0.68), which has been observed by others on land, previous authors have attributed this high variability to intrinsic factors. According to Redfern and Schumann (1994), the high variability may be associated with the positioning of the foot, which varies between individuals and also between each trial.

Furthermore, there are the effects of drag force, buoyancy and turbulent flow, which can promote variability in the Fy component (Fy1 and Fy2) (Miyoshi *et al.*, 2005). The reliability values for the acceptance and propulsion rate were high, which may be explained by some physical properties of water such as drag force, as well as the lower speed that promotes a decrease in gait kinetic parameters (Kyröläinen *et al.*, 2001 and Barela *et al.*, 2006).

In this study the speed was not standardized, which could be a limiting factor, however no differences were found in the duration of the stance phase when comparing the test and retest (Lafuente et al., 2000 and Kyröläinen et al., 2001). In addition, the data did not present a normal distribution, but they were analyzed by Bland and Altman plots and ICC, which may have introduced some bias in to the results. Thus, future studies should standardize the gait speed of the participants and evaluate simultaneously kinematics and joint moments.

5. Conclusion

It is important to be able demonstrate the reliability of the assessment of the components of gait for research and clinical practice. Through accurate knowledge of the GRFs during different exercises, exercise prescription can be made more specific and appropriate for the patient. The test-retest reliability of the kinetic gait parameters of healthy individuals, in the aquatic environment, presented poor to excellent reliability. The vertical and anteroposterior components of gait demonstrated high ICC values, and the vertical component was the most reliable, although some practice effect may have influenced this measure; however, caution should be taken when evaluating the medial-lateral component, as its reliability was low.

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